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Energetic Charged Particle Beams for Disablement of Mines

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***Abstract*—Lawrence Livermore National Laboratory has an ongoing program of weapons disablement using energetic charged particle beams (CPBs). This program combines LLNL's theoretical and experimental expertise in accelerator technology, high energy and nuclear physics, plasma physics and hydrodynamics to fully simulate and measure the effects of high energy, high current electron and proton beams on a variety of weapons, including unexploded ordnance, mines and weapons of mass destruction. We will review work carried out by LLNL, LANL and NSWC over the past few years on detonating sensitive and insensitive high explosives and land mines using high current electron beams, and we will also present computer simulations of electron beam interactions with high explosives. Much of the work presented in this paper has been produced by our colleagues in private industry as well as at military and civilian laboratories. This work has allowed us to project with reasonable confidence the necessary configuration of an electron beam disablement system for clearing land mines in the field. Work in progress at LLNL includes experimental measurements and computer modeling of 20-160 MeV electron beams incident on a variety of wet and dry soils. We are also studying the propagation of electron beams in air in an effort to understand the issues of beam re-pinching, steering, and penetration into the soil and into water. Researchers at LLNL and elsewhere are also developing the next generation of compact high current, high energy accelerators that could be fielded in the next few years for mine clearing. These accelerator systems include newly developed super-insulators for high gradient, high current compact accelerating structures and recirculating induction accelerators. It is anticipated that future electron beam disablement technology, coupled with new detection techniques for buried mines and ordnance, could be an effective means of clearing mine fields in both battlefield and post-battle scenarios. Countermine missions of interest are presented and discussed.**

I. Introduction

Energetic charged particle beams have been studied for many years for military applications [1-4]. In particular, it has been known for some time that electron and proton beams can penetrate significant distances into dense media and deposit significant fractions of their energy in the form of secondary electrons, gamma rays, x-rays, and neutrons. Depending on the energy, current, and time structure of the beam or pulse, energy deposition can lead to heating, melting, material dispersal and thermal shock, and x-ray shock and spall. In the 1970's it was recognized that electron beams could be used to detonate high explosives [5,6]. Initial studies of charged particle beams focused on defeating conventional and nuclear explosives in a number of scenarios [7-10]. Later the Strategic Defense Initiative's LTH-3 program sponsored studies of electron beam effects and lethality for both conventional and nuclear armed cruise missiles for ship defense [11-13]. A number of calculations and experiments have been carried out at LLNL and elsewhere that continue to provide evidence of charged particle beam effectiveness for detonating both sensitive and insensitive high explosives. In the mid-1980's the Army and Navy sponsored programs to demonstrate electron beam detonation of anti-personnel and anti-tank mines as well as sensitive and insensitive high explosives. Experiments were carried out jointly by LLNL, LANL and NSWC at the LANL ECTOR 3 MeV, 35 kA diode facility and the LLNL ATA 50 MeV, 8 kA facility [14,15].

Figure 1 shows a photograph of the detonation of a de-fuzed M14 (US Army) non-metallic anti-personnel mine containing Tetryl carried out at the ECTOR facility, demonstrating that electron beams can indeed be an effective tool to detonate mines. Most recently, in late 1994 experiments have been performed on TNT at the AURORA 10 MeV, 300 kA facility at the Army Research Laboratory by researchers from ARL, LANL and LLNL.

It has been shown experimentally that under the proper conditions both sensitive and insensitive high explosives can be detonated by electron beams. Up until recently, however, the technology to efficiently deliver electron beams of sufficient energy and current in

Fig. 1. Photograph of M14 anti-personnel mine detonating during electron beam exposure at the LANL ECTOR facility.

the field has not been available. Recent developments in compact electron injectors, accelerators and high gradient insulating structures offer the promise of reliable, portable and inexpensive mine disablement systems that can be fielded in the next few years.

II. Charged Particle Beam Interactions in High Explosives

Both energetic electron and proton beams can penetrate significant distances in dense media and deposit energy. Electrons and protons deposit energy in different manners in materials. In general, electrons deposit energy continuously throughout the material as it is traversed by the beam. A "shower" of secondary electrons and gamma rays is generated as the primary electrons lose energy to the surrounding media by ionization and bremsstrahlung radiation. The characteristic length scale for relativistic ($E >> 511$ keV) electron energy loss is given by the "radiation length" of the material, which is a measure of the distance required for the primary electron to lose 1/e of its energy. The radiation lengths for iron, silicon dioxide (quartz) and air (STP) are 1.7 cm, 12.3 cm and ~300 m, respectively.

Clearly energetic electrons can travel long distances through the atmosphere and then penetrate many cm into soils and deposit significant amounts of energy therein – an important requirement for defeating buried mines. Figure 2 shows the penetration depth of electrons in an idealized soil as a function of electron energy.

Unlike electrons, proton and light ions deposit energy in material in a less continuous fashion characterized by a sharp peak (the Bragg peak) at a depth given by the "nuclear interaction length" of the material. The depth required for containment of a fixed fraction of the energy also increases logarithmically with incident particle energy. The interaction length for quartz is 37.58 cm, and for iron is 16.76 cm. In general, protons and light ions may penetrate more deeply into matter but their energy deposition behavior means that one needs to know the depth of the target accurately in order to deliver the proper amount of energy to kill the target. For this reason we have not considered proton and/or light ion beams further for mine disablement applications.

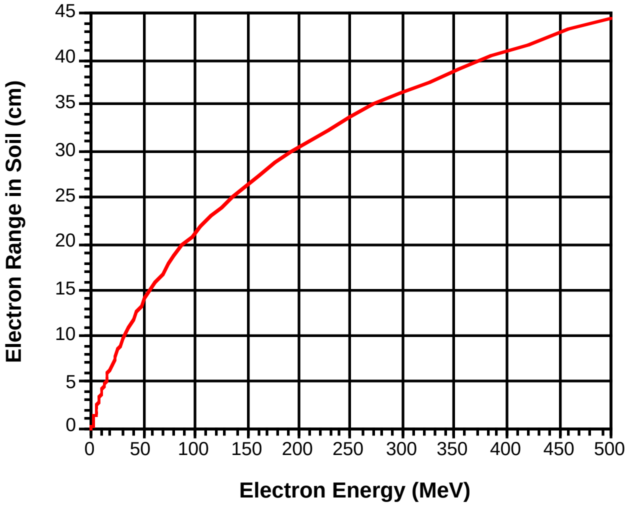


Fig. 2. Penetration of electrons into generic soil as a function of electron energy.

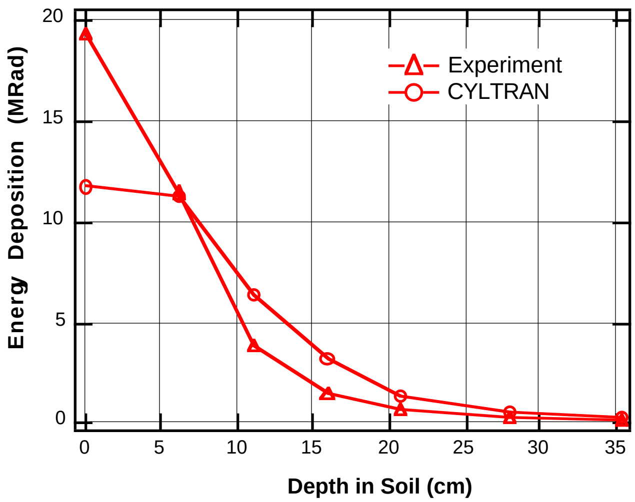


Fig. 3. Comparison of CYLTRAN calculation with experiment for 115 MeV electrons incident on dry sand. The discrepancy at 1 cm depth is due to the electron beam burning the radiochromic film at this point, giving rise to a poor measurement at this point.

We have concentrated our studies on energetic electron beam interactions with high explosives, and we present here calculations in support of experiments carried out in the past using electron beams in a number of configurations of interest to mine disablement. The physics of electron beam interactions in materials is sufficiently well understood and a number of computational tools are available for modeling various buried mine configurations. These computational tools include the Monte Carlo electron-gamma shower code EGS4 developed at the Stanford Linear Accelerator Center [16], ITS3.0 developed at Sandia National Laboratory [17], Albuquerque, and MCNP4 from LANL [18]. All of these codes can model complex electron beam interactions in a variety of materials in 1, 2 and 3 dimensions. A limitation on these codes is that they model interactions of single primary electrons or photons – following the ensuing electron and photon cascade generated by the primary electron or photon to its completion. This is sufficient for most applications where electron beam currents are low, typically much less than 1 A average current. For high current electron beams, these codes cannot properly account for collective phenomena associated with the electron pulse such as the large space charge in the pulse, beam pinching and the effects of the beam on the surrounding media. Collective effects are important in order to understand high current electron beam propagation in the atmosphere and beam pinching and focusing effects in dense media. However, single-particle models have heretofore adequately reproduced (within ~10%) intense beam-material interactions observed experimentally [19].

Figure 3 shows the results of experiments and calculations of 115 MeV electrons incident on dry sand. The measurement was performed at LLNL's 160 MeV electron linear accelerator facility in order to benchmark the 2-D CYLTRAN code, which is part of the ITS3.0 Monte Carlo package. Experiments used radiochromic film to measure both depth and radial dose profiles. Comparison with Monte Carlo shows good agreement at all depths, except at the shallowest point where the beam deposited enough energy to burn a hole through the film (the film measurement was made in the regions near the burn area). Other benchmarking experiments have been performed in the past using arrays of thermoluminescent dosimeters and, in general, agreement between Monte Carlo and experiment is good to about the 10-20% level and in some cases can be much better than this.

We next present a study using CYLTRAN to model an electron beam of 250 MeV on a buried generic TNT target [20]. Figure 4 shows the results in terms of energy deposition for a high current pulse, for two different beam diameters incident on the soil surface. In general one observes the characteristic spread of the beam as it penetrates the soil with contours of 25-75 J/g in the 10 cm TNT zone beginning at 20 cm depth for the 1 cm radius beam and 20-60 J/g for the 2 cm radius beam. There is significant deposition in the soil in front of the TNT. This energy deposition is sufficient to vaporize water and other volatile compounds in the intervening soil, leading to blow-off and dispersal of material.

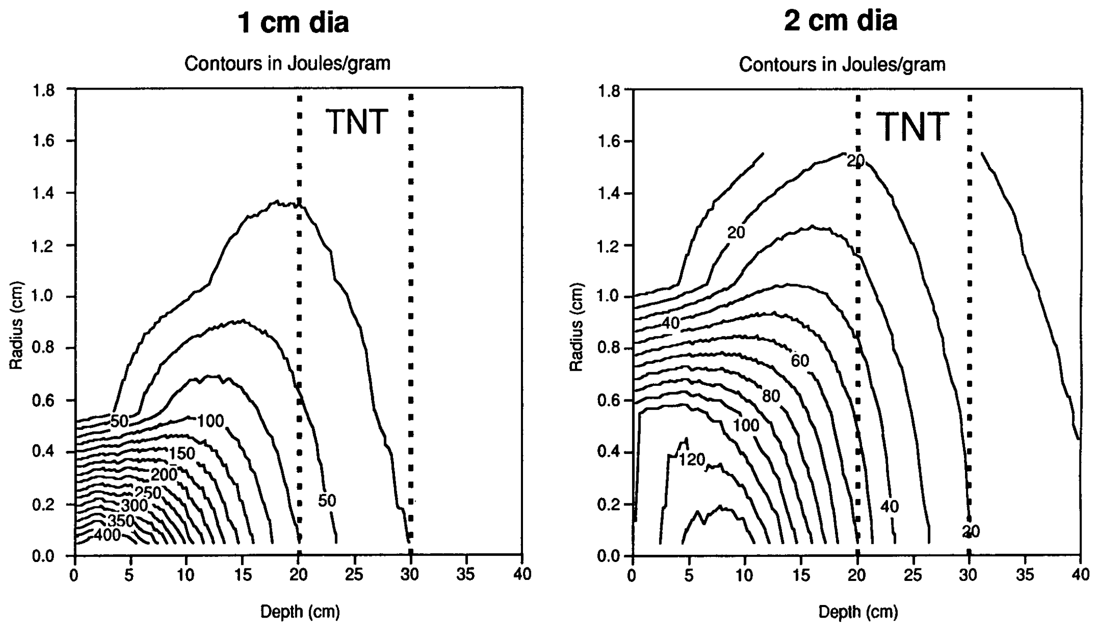


Figure 4. CYLTRAN calculations of a 250 MeV electron beam incident on soil and a buried TNT target, showing the effects of incident beam diameter on overall energy deposition [20].

Under these conditions, multiple pulsing of the electron beam can be an effective means of reaching deeply buried targets and bringing the HE well above thermal initiation threshold. It is also interesting to note that the energy deposited in the TNT can be sufficient to detonate it directly, bypassing any triggers or fuzes. In this way the electron beam offers more effectiveness for detonating mines than other techniques such as explosive nets or mechanical methods that rely on the triggering of the mine's fuze.

As mentioned previously, a number of studies have been carried out over the past 15 years examining electron beam initiation of HE [5-10,14,15]. At LLNL we have successfully combined CYLTRAN predictions of electron beam interactions in HE with 2-D Eulerian hydrodynamic modeling codes and 2-D Lagrangian hydrodynamic codes, e.g., DYNA2D. These codes contain HE equation-of-state information that allows the modeling of state changes and reaction flows in the material under the conditions that are expected from electron beam energy deposition. To illustrate the capability of these codes, Figure 5 shows results of models for electron beams incident on sensitive (PBX-9404, an HMX-based explosive) and insensitive (LX-17, a TATB-based explosive) HE for a particular non-mine application [13]. The code shows that for the sensitive HE a detonation takes place as indicated by the sustained detonation front and velocity.

The insensitive HE in this model did not detonate but instead burns. Experiments have been carried out on HE and IHE that verify the predictions of calculations, in that a minimum energy deposition and a minimum deposition (or priming) volume is required in order to detonate HE using electron beams. The interpretation is that a thermally initiated region propels a subsequent shock initiation of the remaining cold explosive.

New codes developed at LLNL [21] include the ability to model the chemical dynamics and thermal transport in explosives under conditions of extreme temperature and for arbitrary geometries. This code has been applied recently to modeling TNT experiments carried out at the AURORA facility at ARL.

Based on these calculational tools, we can predict with a high degree of confidence that a particular electron beam configuration can be defined that is effective against a particular buried mine configuration.

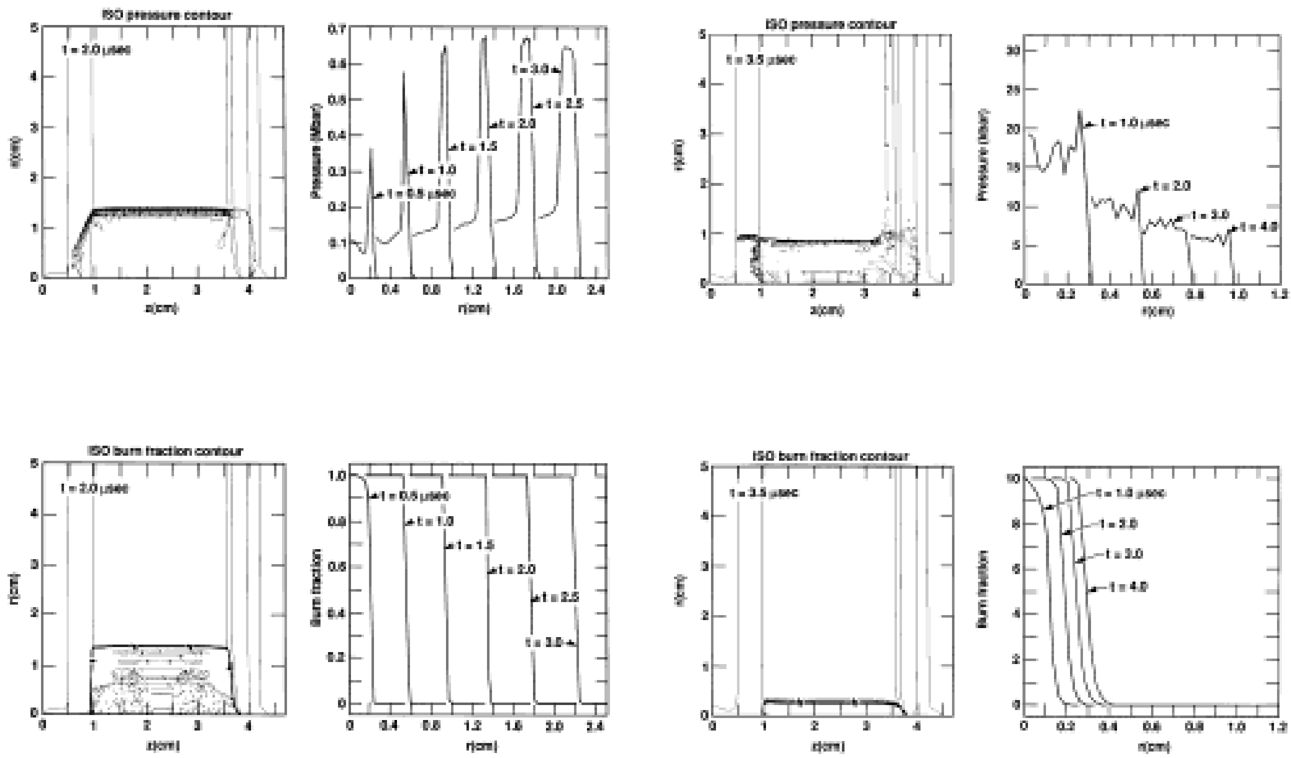


Fig. 5. The four plots on the left show calculations of electron beam initiation of PBX-9404, a sensitive high explosive. Detonation is evident in the well defined detonation front, sustained pressure profile as a function of radius and the constant detonation velocity. The four plots on the right show calculations of electron beam initiation of LX-17, an insensitive high explosive. Detonation does not occur in this particular case.

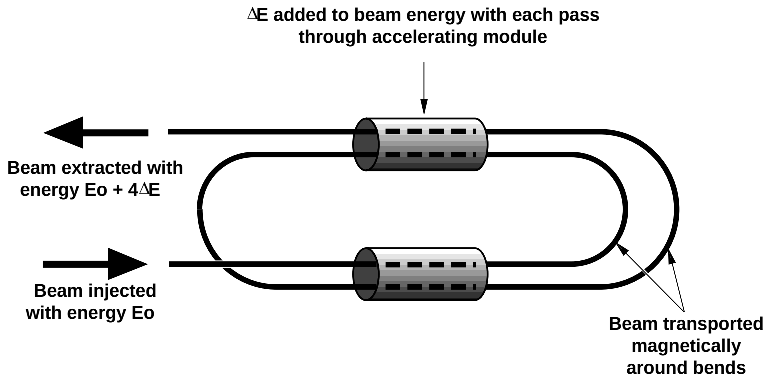
III. Recent Advances in Electron Beam Accelerator Technology

Most charge particle beam accelerators built up to this point are large, complex systems that are not satisfactory for the mission of clearing mines in the field. Accelerator development has advanced slowly over the past years due to the difficulty of increasing microwave power delivery because of RF cavity and insulator material limitations. The basic RF linac has seen little improvement since the building of the Stanford Linear Accelerator Center in the 1960’s, which delivers 50 GeV electrons in a 1.9 mile long structure, corresponding to 16.5 MeV/m accelerating gradient. In addition, RF linacs are limited in the amount of current they can deliver, with 1 A maximum average currents typical.

Another class of electron accelerator is based on the induction accelerator, where a single turn transformer is used to provide a kick to an electron pulse as it traverses through the induction element. Induction linacs typically offer lower energy but much higher peak currents compared to RF linacs The Advanced Test Accelerator (ATA) at LLNL is an example of an induction linac. It consisted of 200 induction cells each delivering 0.25 MeV in a 70 m long accelerator. The ATA (now mothballed) was capable of generating 50 MeV electron beams with currents up to 8 kA.

IV. The SLIA/ISA Concept

Promising developments have been made in the area of compact induction accelerators. The concept favored at this time by ARPA, the Army and the Navy is the Spiral Line Induction Accelerator (SLIA), coupled to an Induction Synchrotron Accelerator (ISA). The SLIA/ISA concept is under development at Pulse Sciences, Inc. [22]. A SLIA has demonstrated 5.5 MeV, 10 kA operation with full-turn-transport and two passes through the accelerating section. Figure 6 shows a schematic of the SLIA and photograph of the device. Current activities include increasing the energy to 9.5 MeV and demonstration of a repetitive operation power system for countermine applications.



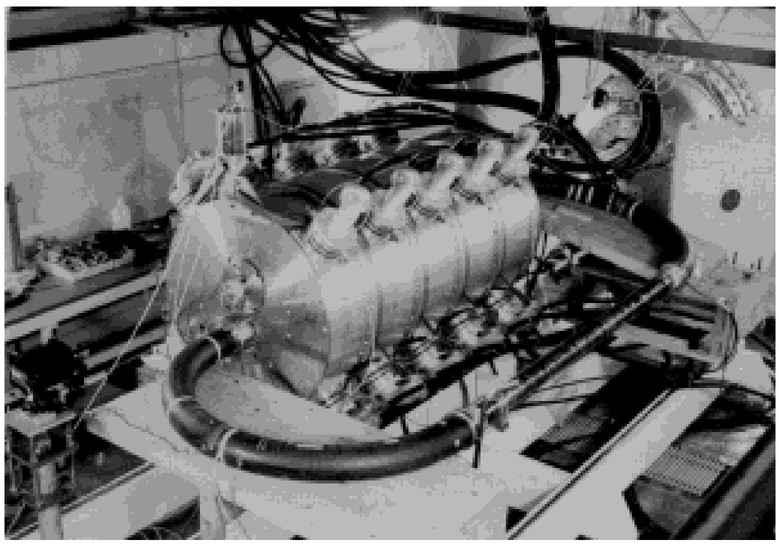


Fig. 6. Schematic and photograph of the Spiral Line Induction Accelerator under development at Pulse Sciences, Inc. [22].

V. ARPA/Army/Navy Memorandum of Understanding

An ARPA/Army/Navy 5-year MOU has as a goal the development of a technology to clear buried mines by FY99 by performing a proof of concept experiment using the SLIA as the injector to a high energy accelerator (the ISA) to boost the beam energy to the 150-250 MeV range. The SLIA can also be used as a low energy mine detection beam. The simple nature of these accelerator structures allows for a robust system. Power supplies, beam conditioning and steering are easily addressed issues once the beam parameters are chosen.

Figure 7 shows the SLIA/ISA concept together with a notional concept of an electron beam delivery system. The delivery system contains sensor packages designed to detect mines prior to detonation. The accelerator can be operated in a low current mode that scans the ground ahead of the mineclearing system with an x-ray beam. In a concept called MIDEP [23], the x-rays interact with the stable nitrogen isotope, nitrogen-14, that is found in all modern explosives via a photonuclear reaction to produce the radioactive isotope nitrogen-13, which then decays via positron emission, producing annihilation photons which can be easily detected. In a separate concept, a low energy electron beam could be utilized directly to heat the ground, producing IR signatures due to local heating anomalies when high explosive, plastics, or other materials in the buried mine are interrogated by the electron beam. Once a potential mine is identified the current can be increased to deposit energy sufficient to detonate the HE.

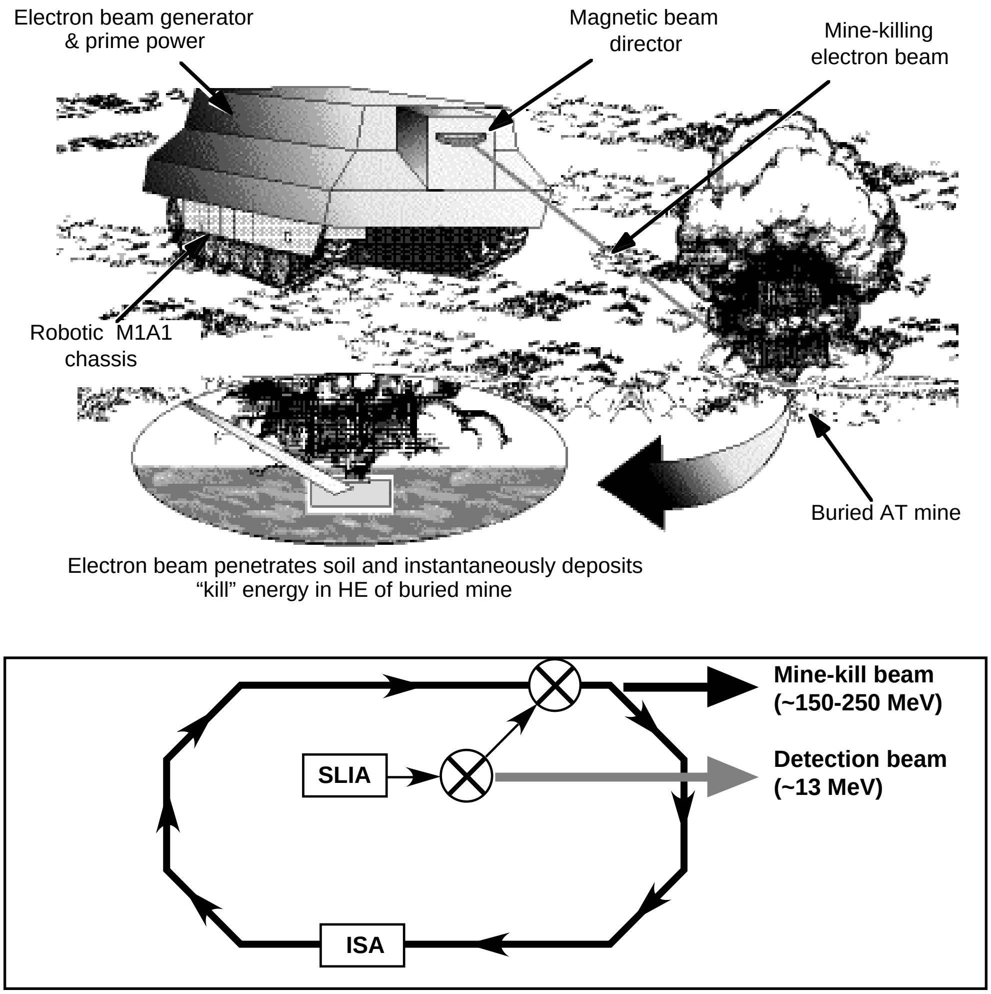


Fig. 7. Notional concept of an electron beam system for detecting and clearing land mines and schematic of SLIA/ISA system (return-radiation sensor system not shown).

VI. Emerging Accelerator Technologies

At the present time a new accelerator concept called the two-beam or relativistic klystron is being studied. This accelerator combines the induction linac with an RF linac, with the induction linac used to generate the RF drive power. This concept has been recently been approved for funding and the first generation prototypes are under construction by a joint LLNL/Lawrence Berkeley Laboratory collaboration.

While the two beam accelerator offers promise for the next generation of large laboratory-based linacs for basic research (the Next Linear Collider, or NLC), it is unlikely to be easily adapted to the mission of clearing mine fields in the short term.

Another development is in the area of super-insulator technology, which combines dielectrics and metals in alternating layers to provide structures capable of extremely high standoff voltages. Work on super-insulators is taking place at LLNL and elsewhere and promises to allow very high accelerating gradients in short, high current pulses [24].

Using advanced compact accelerator technologies such as the above it is probable that within the next few

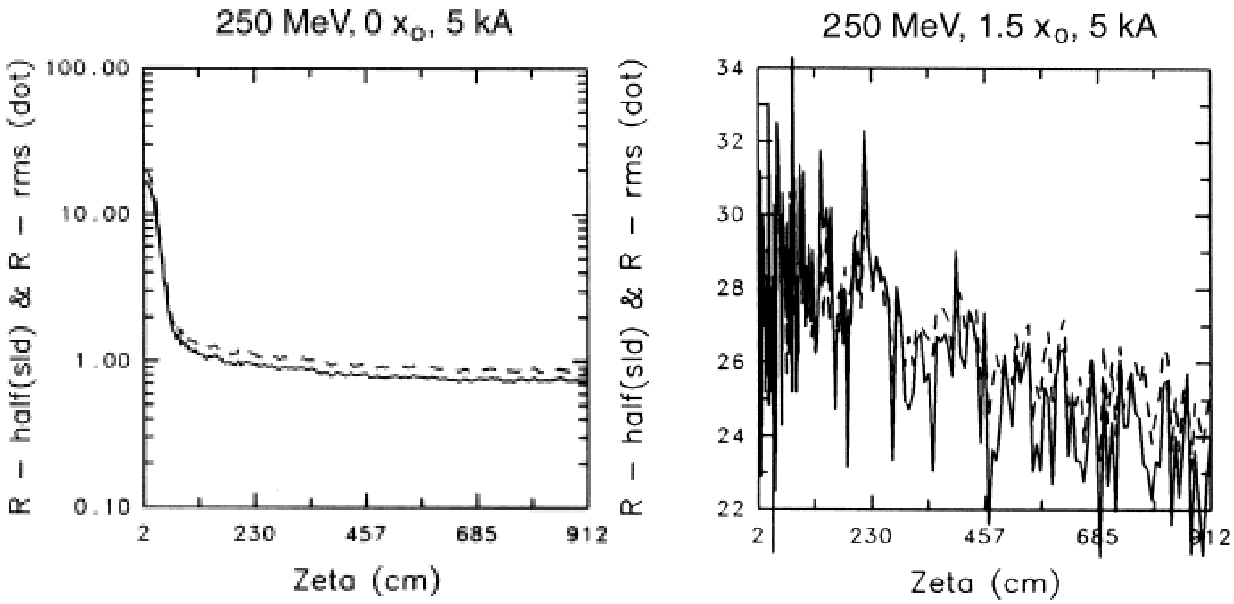


Fig. 8. BEAMFIRE calculation of electron beam propagation showing stable and unstable propagation conditions. The vertical axis is the ratio of the beam initial radius to its propagation radius at a particular point (solid line is beam half-width and dashed line is beam RMS width). The horizontal axis is a measure of the distance from the beam front. Thus the figure on the left shows stable propagation for about 900 cm at this instant in time with beam trumpeting occuring only in the last 50 - 100 cm. The figure on the right shows the detrimental effect of launching the beam through 1.5 radiation lengths of material. Note the change in scale in the right hand figure from log to linear and also the suppressed zero.

years a ~200 MeV high current linac could be implemented in a physical space that could fit onto a standard tank chassis.

VII. Current and Future Activities in Electron Beam Mine Detection and Clearing

There are currently a small number of minimally funded activities studying electron beam interrogation and detonation of mines. While it has been recognized that electron beams are effective against mines, the lack of a fieldable machine and a mission concept has prevented significant funding from being applied to the development of a viable system. Instead motivated individual researchers and laboratories have applied internal funding and small amounts of money from the Army and Navy to study the problem.

Last year's MOU for $6M was signed between the Army, the Navy and ARPA to provide funding for both accelerator development and effects studies. The bulk of the funding has gone towards accelerator development and only a small amount has been devoted to experiments and calculations in support of systems development. It is clear that more work is needed in the latter area, particularly to address the effects of beam propagation, intervening materials, wet and dry soils, etc. Additionally the efficacy of electron beams for detonation of surf-zone and underwater mines is completely unexplored and could prove to be viable.

In the area of electron beam modeling, new Monte Carlo codes are becoming available that calculate fully coupled electron-photon-neutron particle generation and transport. Neutron heating and transport can become an important issue for beam energies above 20 MeV. Neutron generation and capture can be exploited for detection of buried mines. Collateral effects of electron beams also need to be understood. These include effects on operating personnel in the field, and radiation effects on the environment, including radioactivation of elements in the soil as well as sterilization of biological systems in the soil. Preliminary measurements of 115 MeV electrons on dry sand indicate that activation products are short-lived, with few-second to few-minute half-lives. Soil sterilization using scanned electron beams may actually have commercial applications in agriculture, and electron beams are already commercially available for sterilizing medical apparatus and food products.

Beam propagation in the atmosphere is another area that is being addressed using newly developed codes that combine the physics of electron interactions in the

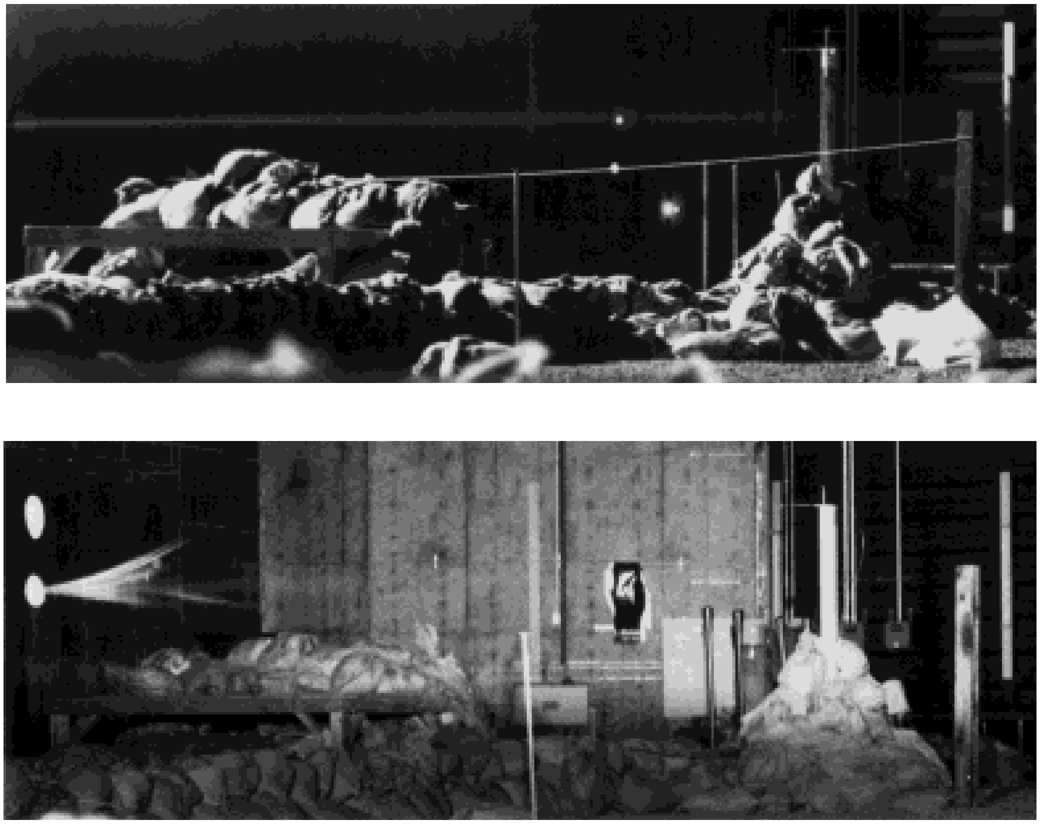


Fig. 9. Photographs of the ATA at LLNL demonstrating stable and unstable propogation of a 50 MeV, 8 kA electron beam in the atmosphere. In the upper photograph the beam is observable as a faint horizontal line approximately 1/3 from the top. The beam is emerging from the left and is propagating approximately 20 meters. The lower photograph shows the severe trumpeting of the beam under improper launch conditions.

atmosphere with the effects of high current density. The BEAMFIRE code, developed by researchers from LLNL and LBL, has been used to model energetic high current electron beam propagation in air [25]. Figure 8 shows results from this code that indicate beam refocusing (pinching) can occur upon extraction from the accelerator with reasonable propagation lengths of interest for a proper standoff mine clearing system.

Experimentally, the ATA demonstrated that intense energetic electron beams can be made to propagate many meters in air without dispersion. Figure 9 shows a photograph of a properly conditioned ATA beam propagating a distance of about 20 m before dissipating. Also shown is an example of instability in beam propagation if the electron beam is not properly prepared for launch into the atmosphere.

As was mentioned earlier, there is no single accelerator available yet that combines both high energy and high current operation in a single beam. Until such a machine becomes available, a number of machines are being used to understand the separate effects of high energy and high current electron interactions in soils, HE and mines. LLNL's 160 MeV linac is a unique resource in the US for high energy effects studies in that it is the only remaining linac that is operated full time for use as both a basic research and weapon effects machine. The facility includes a number of large experimental caves and neutron time-of-flight lines. Other linacs such as the ORELA facility at Oak Ridge and the Naval Post-graduate School Linac also offer the capability for high energy electrons. Lower energy, higher current machines include the AURORA facility, LLNL's FXR (17 MeV, 2 kA in a 70 ns pulse, with 2-pulse capability), and PIXY (a 6 MeV diode machine, similar to ECTOR) at LANL. We have shown that a combination of experiments at these machines can yield valuable information for input to system models to evaluate the effectiveness of electron beams for destroying mines.

VIII. Charged Particle Beam Countermine Missions of Interest

Several countermine missions are envisioned that are well-suited to the capabilities of a Charge Particle Beam Counter Mine (CPB-CM) system. These include:

1. Route Clearing - clearing established routes to ensure Lines of Communication (LOC)

2. Area Clearing - clearing defined minefield where the area has been secured and the entire minefield is to be neutralized

3. Assault Breaching - penetration of the minefield while under enemy fire where speed of advance is critical; CPB-CM system could support primary forward breachers (e.g., plows, rakes and flails)

Area clearing as defined above applies to both military and non-military operations, for example, clearing of mines in third world countries where it is needed to restore land to agricultural and residential use.

As a part of the evaluation of CPBs for the above missions, a system engineering study has been performed by Jason Associates Corporation [20] that evaluates effective speeds, and power requirements, under assumptions of sensor performance and false alarm rates. Results of the analysis include system advance rate and power consumption as a function of sensor performance, mine burial depth, and beam energy. I summarize here the main points of this study:

1. Sensor performance (detection rate, false alarms) is an important system driver. False alarm rates less than $0.01/m^2$ are needed.

2. System advance rate is not very sensitive to either mine burial depth or mine detonation threshold.

3. Advance rates of a few mph are possible with near-term sensor performance goals.

4. High advance rates (> 8 mph) are possible if more advanced sensor performance becomes available.

5. Average system power requirement is in the range of a few hundred kW under most conditions.

6. For a given false alarm rate there exists a detection mode speed above which additional performance gains are not achieved.

7. Beam energy of about 250 MeV is optimal although beam energies as low as 150 MeV yield acceptable performance.

8. System standoff from the mine in kill mode is optimal at about 5 m.

IX. Summary and Recommendations

It is clear that the mission of CPB-CM is in an evolutionary state as the capabilities of the system are demonstrated over the next few years. Vital to the development of CPB-CM is the development of better working relationships with the user(s) in order to guide the development of the system. Part of this relationship includes regular top-level situation-audits of CPB technology for countermine missions as well as the receipt of guidance and data on potential CPB-CM mission area requirements and alternative systems that might also address those missions. In this way actions can be identified and a schedule developed to produce a roadmap to assess CPB technology utilization in countermine mission areas.

X. Relationship to Other Efforts

While this paper has concentrated on charged particle beam disablement of mines, at LLNL a number of activities in the area of mine detection and disablement are being coordinated in a Mine Warfare Working Group chaired by Dr. Milton Finger. A number of presentations are being made at this Symposium by other LLNL researchers and collaborators. The LLNL Mine Warfare Working group meets regularly to discuss and coordinate mine-related activities at LLNL, to identify potential new programs as they are announced, with the goal of developing the necessary combination of mine detection and clearing technologies to solve the needs of the military and civilian agencies involved in this important mission. LLNL maintains a mine field test area with a number of different types of anti-personnel and anti-tank mines at the Nevada Test Site for fielding and testing both detection and disablement concepts. We hope that this Symposium will spark the beginning of a new era in mine warfare and countermine activities. We look forward to the establishment of new partnerships and a new level of cooperation between the Army, Navy, ARPA, Industry and the National Laboratories.

Acknowledgments

I would like to acknowledge the contributions of a number of researchers whose work is presented here and in the references. In particular, Dr. Adrian C. (Chip) Smith and Dr. Jay Boudreau of Jason Associates Corporation have been long-standing proponents of electron beam detection and disablement of land mines and have provided me with a wealth of information on the system concepts touched upon only briefly in this paper. Dr. Smith and Dr. Nancy Chesser of Directed Technologies, Inc., also provided me with extremely useful comments and suggestions regarding many of the topics in this paper. Dr. Sidney Putnam of Pulsed Sciences, Inc. graciously provided me with the photograph of the SLIA. Mr. Klaus Kerris of ARL and his colleagues have performed the most recent tests of HE detonations at ARL. Dr. Tom Phillips and Mr. Joe Mauger performed the soil exposures and data analysis at the LLNL 160 MeV Linac. Much of the early work in modeling electron beam interactions in HE was performed by LCDR Steven Miller (Ret.), while serving as a Military Research Associate at LLNL between 1987 and 1990. This work was performed by LLNL under the auspices of the USDOE Contract number W-7405-ENG-48.

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